



The Early Life of Stars

Violent collisions of gas dominate the childhood of stars. Eventually nuclear fusion begins, enabling mature stars to burn steadily for billions of years.

by Steven W. Stahler

Looking up at a clear night sky, far from city lights, one sees that the universe is filled with stars. Somehow nature has managed to create untold numbers of these objects--an estimated 100 billion in the Milky Way alone. Furthermore, stars continue to be born, 10 to 20 billion years after the universe began. How are stars created? What changes does a young star undergo before it settles into the relatively stable state now exhibited by the sun?

From a physicist's perspective, a star is a ball of hot gas held together by its own gravity. The heat and pressure generated by internal nuclear reactions--chiefly the fusion of hydrogen into helium--prevent the star from collapsing under the gravitational force. This relatively simple system has a well-defined lifespan. It begins with the star's condensation from a diffuse cloud of interstellar gas and ends when the star, having exhausted its nuclear fuel, fades from sight as a white dwarf, neutron star or black hole.

From this description, it might seem that detailing the formation and early evolution of stars should present no essential difficulties. But the subtle ways in which gravity and thermal pressure interact cause young stars to behave in a manner that sometimes defies intuition. Consider, for example, the evolution of luminosity, the amount of energy emitted by the stellar surface per unit time. The internal temperature of a young star is too low to fuse hydrogen, so its luminosity would also be expected to be relatively low. It might increase when the fusion of hydrogen begins and then gradually fade.

In fact, a very young star is extremely bright. Its luminosity decreases as age advances, reaching a temporary minimum at the time of hydrogen ignition. The early life of stars involves a rich variety of physical processes, some of which remain poorly understood. Only within the past two decades have astronomers begun to piece together, through theory and observation, a coherent and detailed picture.

Stars condense under their own gravity from large, optically invisible clouds found throughout the disks of spiral galaxies. Such aggregates are called giant molecular cloud complexes. The term "molecular" refers to the fact that the gas consists mostly of hydrogen in its molecular form [see "Giant Molecular-Cloud Complexes in the Galaxy," by Leo Blitz; SCIENTIFIC AMERICAN, April 1982]. The complexes are the most massive structures in the galaxy, sometimes measuring more than 300 light-years across.

Closer inspection reveals that stars develop from isolated condensations within the giant molecular cloud complexes. Such condensations are called dense cores. Philip C. Myers of the Harvard-Smithsonian Center for Astrophysics, who coined the term in 1983, was the first to observe their properties systematically and to emphasize their role in star formation.

Astronomers investigate the properties of dense cores by using large radio telescopes, the only instruments capable of detecting the weak, millimeter-wavelength radiation that the clouds emit. The radiation comes not from the molecular hydrogen but from the trace amounts of other substances in the cores, such as carbon monoxide and carbon monosulfide. The emissions from these trace gases reveal that a typical dense core has a diameter of a few light-months, a density of 30,000 hydrogen molecules per cubic centimeter, and a temperature of 10 kelvins [see illustration on page 53].

From these numbers, investigators inferred that the gas pressure in a dense core is just about the right magnitude to withstand the compressive force of the core's own gravity. To form a star, therefore, the core must collapse from a marginally unstable state--that is, one in which gravity is only slightly stronger than pressure.

How the core itself condensed from its parent molecular cloud complex to arrive at this marginally unstable state is still not well understood. Nevertheless, astrophysicists had the tools to model stellar formation even before the discovery of dense cores. In the 1960s theorists had used computer simulations to determine how clouds in unstable states collapse.

Although the simulations assumed widely varying initial conditions, each one

showed that clouds that are not violently unstable collapse in an inside-out manner. That is, material at the center first enters into a true free-fall collapse while the outlying gas remains static. Gradually the region of collapse spreads outward through the rest of the cloud.

Deep within the collapsing region, a star begins to form from the collisions of gas. The star itself is only about one light-second in diameter--one ten-millionth that of the dense core. For a star of such a relatively small size, the overall pattern of collapse is insignificant. What counts is the mass accretion rate.

This rate is the amount of matter per unit time crossing an imaginary spherical shell near the center of the cloud. In his elegant and influential 1977 paper, Frank H. Shu of the University of California at Berkeley demonstrated a remarkable result: the mass-accretion rate depends solely on the initial cloud temperature. The higher the temperature, the greater the rate of accretion. Shu's result indicates that an amount of mass equal to the sun's accumulates at the center of a collapsing dense core in 100,000 to one million years.

The object forming at the center of the collapsing cloud is known as a protostar. The modern theory of protostars began to take shape in 1969, when Richard Larson of Yale University was able to observe stellar buildup in a computer simulation of cloud collapse. Researchers developing Larson's pioneering work have found an advantage in conceptually separating the protostar from the cloud as they model the collapse. In other words, investigators examine the protostar in isolation as an ordinary star with an extraordinary outer boundary condition--the incoming accretion flow.

Astronomers running these simulations can vary the properties of the accretion flow to gauge its effect on the evolution of the protostar. In 1980 Shu, Ronald Taam of Northwestern University and I first used this approach to establish the properties of protostars of about one solar mass. More recently, in collaboration with Francesco Palla of Arcetri Observatory in Florence, I have turned to the method once again to study more massive protostars.

Through such simulations, astronomers have now developed a model that describes the protostar phase. Workers have found that the incoming gas hits the protostar at a very high speed, so high that it cannot decelerate gradually before reaching the stellar surface. Instead it encounters a strong shock front (a sharp transition to very high pressure) that rapidly halts the gas. Within the shock, the gas is heated to nearly one million kelvins. The gas quickly cools by radiation to about 10,000 kelvins and settles down, layer by layer, to form the protostar.

The shock front explains why young stars are so luminous. If a protostar attains one solar mass, the luminosity that the gas generates when it encounters the shock front exceeds solar brightness by a factor of six to 60. Thus, the acute brightness of these young stars stems not from nuclear fusion, as in ordinary stars, but from the kinetic energy of matter as it is pulled in by gravity.

The luminosity from protostars is observable, but not with optical telescopes. All the gas in interstellar space, including that which forms stars, contains "dust," a mixture of solid particles of submicron size. As photons stream outward from the shock front, they eventually encounter massive amounts of these dust grains falling in along with the gas of the original dense core.

The dust cannot reach the protostar surface, because the intense heat from the shock front vaporizes it. Astronomers refer to the volume of space within which the dust is vaporized as the opacity gap. Farther upstream, beyond the opacity gap, temperatures are low enough to enable the grains to exist. The cold grains absorb the shock-generated photons and reemit them at longer wavelengths. These long-wavelength photons are in turn absorbed by dust grains lying farther away.

The photons thus tortuously make their way through the cloud material, until their average wavelength lies deep in the infrared region of the electromagnetic spectrum. At a radius that Shu, Taam and I call the dust photosphere, located a few light-hours from the protostar, the photons have too long a wavelength to be absorbed by the dust and can finally fly unimpeded to earth-based infrared telescopes.

Despite the capabilities of modern detectors, astronomers cannot definitively say that telescopes have actually recorded the infrared signals of protostars. After its launch in 1983, the Infrared Astronomical Satellite generated hundreds of thousands of images of pointlike infrared sources of radiation [see "The Infrared Sky," by Harm J. Habing and Gerry Neugebauer; SCIENTIFIC AMERICAN, November 1984]. Many sources appear to be located deep within the radio-imaged dense cores; some must undoubtedly be protostars. The uncertainty arises because detectors cannot distinguish the protostars from somewhat older stars, also buried in dust and gas.

For a positive identification, infrared or radio telescopes must be able to detect the Doppler shift of spectral lines very close to an infrared point source. The Doppler shift would represent the actual motion of the gas as it falls onto the stellar surface.

Once the protostar accretes sufficient material to reach a few tenths the mass of the sun, the temperature at the center becomes sufficient to induce nuclear fusion.

Fusion in protostars, however, is quite different from that of main-sequence stars--that is, middle-aged stars like the sun existing in a long-lived state of equilibrium. The primary reaction that powers a mature star involves the fusion of hydrogen nuclei.

Hydrogen is the most common chemical constituent of the universe. The big bang created this element primarily in its normal isotopic form, as an atom whose nucleus consists of a single proton. But about two out of every 100,000 hydrogen nuclei consist of deuterium, a nucleus of one proton and one neutron. Deuterium persists today in the interstellar gas that becomes incorporated in new stars.

Remarkably, this tiny impurity plays a dominant role in the life of protostars. The interiors of protostars are not yet hot enough to fuse ordinary hydrogen, a reaction that occurs at about 10 million kelvins. But protostars can easily attain, as a result of the compressive force of gravity, the temperature of one million kelvins required to initiate the fusion of deuterium, which also liberates large amounts of energy. The protostellar material is too opaque to transmit this energy by radiation. Instead the star becomes convectively unstable: bubbles of gas heated by the nuclear fire rise up toward the surface.

This upward motion is balanced by the sinking of cooler gas toward the center. The same sort of convective circulation, on a much smaller scale, occurs in the air in a radiator-heated room. But in a protostar, the circulating eddies drag down fresh deuterium that has landed on the surface. These deuterium atoms are quickly transported to the center, where they fuse together and release more heat. Thus, the return stroke of the convection cycle continuously resupplies the fuel needed to maintain both burning and convection.

If the protostar gains enough matter to become about twice as massive as the sun, the convection cycle begins to operate in a slightly different manner. Palla and I recently found that a thin shell of gas in the interior region becomes transparent enough to transport heat through radiation rather than convection. Neither rising nor sinking gas can penetrate this radiative barrier. Consequently, fusion quickly consumes all the deuterium inside the barrier. Fresh deuterium falling onto the protostar piles upon its surface. The compressed surface layers become hotter until they, too, ignite the deuterium, which then burns in a shell overlying the depleted interior. Hot bubbles rise up from this burning shell, make their way to the surface and then sink back down to the shell, completing the refueling cycle.

Despite the small concentration of deuterium nuclei, the heat released by their fusion has a considerable impact on the protostar. The chief effect of the burning of deuterium is to cause the protostar to swell. Because convection efficiently spreads

the heat, deuterium burning enlarges each protostar to a characteristic size, determined by the object's mass. A protostar of one solar mass has a radius five times that of the present sun. A protostar of three solar masses, in which deuterium burns in a subsurface shell, swells even more dramatically: its radius is 10 times the solar value.

A typical dense core encompasses more mass than the star it ultimately produces. Therefore, some mechanism must expel the extra mass and halt the accretion. Most astronomers have now become convinced that a strong wind erupting at the surface of the protostar is responsible. The wind blows back the incoming gas and eventually disperses the entire dense core.

The wind idea did not come from any theoretical calculation. The phenomenon was suggested to surprised theorists by widespread observation of molecular gas streaming away from infrared sources of radiation [see "Energetic Outflows from Young Stars," by Charles J. Lada; *SCIENTIFIC AMERICAN*, July 1982]. The agent of the outflow would appear to be the protostellar wind. This wind, which has not yet been directly observed, must drive off matter and energy at a vastly greater rate than do winds emanating from main-sequence stars. The cause of the protostellar wind is one of the deepest mysteries in the study of young stars.

Once the dense core disperses, the exposed object, now optically visible, is known as a pre-main-sequence star. Like a protostar, a pre-main-sequence star is highly luminous. Once again, gravity rather than nuclear fusion accounts for the luminosity. The pressure within the star prevents it from going into a true free-fall collapse. The heat maintaining this pressure, however, is radiated from the stellar surface, so that the star shines very brightly and shrinks slowly.

Like protostars, pre-main-sequence stars are convectively unstable. The underlying physics, however, is quite different. In general, convection in a star begins whenever the temperature drops very rapidly from the center to the surface. In protostars, deuterium burning at the center creates the convection cycle. But by the time a protostar evolves to the pre-main-sequence stage, it has exhausted its supply of deuterium.

The great luminosity of pre-main-sequence stars accounts for the steep temperature gradient within the star. The high levels of radiant energy given off cool the outer layers quickly, whereas the interior region remains insulated by the overlying matter. As the star ages and luminosity diminishes, the region of convective instability decreases. In the present sun, convection still survives over the outer 30 percent of the radius. The rising and sinking eddies create the granulated texture of the solar surface.

As the star becomes more compact, its internal temperature steadily rises and eventually reaches about 10 million kelvins. At this point, ordinary hydrogen begins to fuse into helium. The heat released from the fusion builds up the pressure to halt the contraction, and the star enters the main sequence. It took our sun, a typical hydrogen-burning star, about 30 million years to contract from its large protostar radius to its present size. The heat released from the subsequent hydrogen fusion has maintained this size for about five billion years.

The descriptions of stellar evolution I have just given are consistent with physical theories and known nuclear processes. But theory needs to be supported by data. The data consist of measurements of the properties of many stars at different stages of their evolution. The most convenient way to express such data is to display graphically the evolution of optically visible stars in the Hertzsprung-Russell (H-R) diagram.

The H-R diagram is a graph that plots stellar luminosity on the vertical axis and surface temperature on the horizontal axis. Main-sequence stars like the sun, which fuse ordinary hydrogen, lie along a diagonal curve. Theoretical calculations show that the luminosity and surface temperature of a hydrogen-burning star--and thus its position on the curve--depend only on its mass.

This theory agrees well with observation. Astronomers determine the luminosity of a star by measuring its brightness (provided that the distance to the star is also known) and deduce the surface temperature by analyzing the star's spectrum. When one measures these two quantities for a given cluster of stars and plots the data on the H-R diagram, most of the stars indeed lie along the theoretical main-sequence curve.

Because a pre-main-sequence star is more luminous than a main-sequence one of the same mass, it will lie above the main-sequence line in the H-R diagram. The luminosity decreases with time because the shrinking of the star diminishes the surface area from which the radiation can be emitted. As a result, the star's representative point slides along a definite path that is the same for all stars of its mass. Astronomers refer to this path as a Hayashi track, in honor of Chushiro Hayashi of Kyoto University, who first calculated the properties of pre-main-sequence stars in the early 1960s.

Observations of nearby young clusters--that is, stars with a lot of interspersed molecular gas between them--have revealed that many of the stars lie above the main sequence. Those that lie near Hayashi tracks corresponding to one solar mass or less are known as T Tauri stars. Their more massive counterparts are called Herbig Ae and Be stars. (The latter group was named for George Herbig of the

University of Hawaii, the astronomer who pioneered the observational study of young stars.)

Although theorists are gratified that many stars lie above the main sequence, it is a more difficult matter to prove that these stars are actually descending their appropriate Hayashi tracks. Recall that deuterium burning in protostars gives them a definite radius for each value of mass. In 1983 I used this relation, together with the set of known Hayashi tracks, to make a prediction: once pre-main-sequence stars become optically visible, they should all appear along another curve in the H-R diagram. From this curve, called the birthline, each star descends along its appropriate Hayashi track to the main sequence.

Observations appear to bear out the idea of the birthline. In 1979 Martin Cohen and Leonard V. Kuhi of Berkeley published a systematic study of hundreds of T Tauri stars. In 1984 Ulrich Finkenzeller of the Landessternwarte Konigstuhl (the state observatory) in Heidelberg and Reinhard Mundt of the Max Planck Institute for Astronomy presented a similar survey for the rarer Herbig Ae and Be stars. The measured luminosities and surface temperatures of these stars lie on or below a well-defined boundary in the H-R diagram. The boundary coincides well with the theoretical birthline. Furthermore, those visible stars at the center of molecular gas outflows also lie along the birthline. Their location in the diagram confirms the fact that the outflow phase is associated with the beginning of pre-main-sequence contraction.

Palla and I have shown that the birthline must intersect the main sequence at some point. We calculated that the two curves meet at a position corresponding to a stellar mass of eight solar masses. In physical terms, the finding means that any star more massive than this critical value actually begins to fuse ordinary hydrogen while its parent dense core is still collapsing onto its surface. These massive stars should therefore never exhibit a visible pre-main-sequence phase. So far this prediction also seems to be in accord with existing observations.

Despite this encouraging success of the theory, many of the known properties of young stars are still not entirely understood. Most young stars, for example, are irregular variables: their luminosities fluctuate over periods ranging from hours to months. The spectra of many T Tauri stars, the group that has been particularly well monitored, show far more infrared and ultraviolet radiation than do main-sequence stars of similar mass. Yet Frederick Walter of the State University of New York at Stony Brook has found that other T Tauri stars, with very similar masses and ages, exhibit almost no excess emission. Finally, there is much evidence for strong stellar winds. These winds could well be the remnants of the much more powerful ones believed to end the protostar phase.

The models describing the birth of stars indicate an important by-product: the circumstellar disk. Investigators believe such disks provide the raw materials from which planetary systems form [see "Worlds around Other Stars," by David C. Black; SCIENTIFIC AMERICAN, January]. A disk forms because not all the material collapsing inside a dense core directly joins the protostar. Whatever process formed the dense core almost certainly imparted some degree of rotation as the collapse began. Within the rotating core, the gas with the highest angular momentum lies farthest from the polar axis. As the region of collapse spreads outward, it engulfs the more distant gas. This material begins to fall inward but misses the protostar. The gas goes into orbit around the protostar, assuming the form of a circumstellar disk.

The manner in which the direction of the falling gas gradually shifts from the protostar to the disk was first worked out mathematically in 1976 by Roger Ulrich of the University of California at Los Angeles and, independently, in 1981 by Patrick Cassen and Anne Moosman of the National Aeronautics and Space Administration Ames Research Center. Cassen and Moosman also first investigated the theoretical physical properties of disks, such as their sizes and surface densities. Great interest currently exists in extending their work to the older disks surrounding pre-main-sequence stars. This focus has arisen not only because such research promises to illuminate how planets form but also because recent observational evidence indicates the existence of disks.

One kind of evidence consists of actual images that show circumstellar matter around young stars. In 1987, for example, Steven Beckwith of Cornell University and Anneila Sargent of the California Institute of Technology detected extended emission from carbon monoxide gas surrounding the T Tauri star HL Tau. They attributed this emission to a low-mass disk with a diameter of several light-weeks.

Another kind of evidence for disks is more indirect and hence more controversial. The evidence is actually a deduction: theorists assert that certain observed properties of T Tauri stars can best be explained by the presence of disks. Following the original suggestion in 1974 by Donald Lynden-Bell and James Pringle of the University of Cambridge, investigators have commonly attributed both the infrared and ultraviolet excesses of these stars to luminous disks that are continuously transporting mass onto their host stars.

Material must somehow lose angular momentum if it is to spiral onto the star. Lynden-Bell and Pringle assumed that an unspecified friction exists throughout the disk. As two adjacent rings of gas rub against each other, the friction would cause the inner, more rapidly rotating ring to slow down and contract, just as the orbit of a satellite above the earth slowly decays because of atmospheric drag.

According to this picture, the excess infrared emission represents the heat generated by the friction. The ultraviolet radiation, on the other hand, is supposed to arise from a narrow, hot region between the disk and the star, in which an even stronger frictional force brakes the orbiting gas. Using models of this kind, workers have successfully matched many spectral features of T Tauri stars. They are Lee W. Hartmann and Scott Kenyon of the Harvard-Smithsonian Center for Astrophysics, Gibor Basri of Berkeley and Claude Bertout of the University of Paris.

Yet despite the best efforts of theorists over many years, no plausible explanation exists for the internal friction that these models posit. Calculations show, for example, that ordinary molecular viscosity is far too small to cause appreciable spiraling of the gas onto the central star.

In my opinion, the failure to explain the source of the friction implies that the underlying model is inadequate. A better approach may be to drop the assumption of internal friction altogether. Theorists should look again at the structure of disks that can actually form during the collapse of rotating dense cores. During the past several years, my students and I have undertaken just such an investigation. Thus far the models of disk formation we have obtained are different from the frictional ones.

All current observations of disks, both direct and indirect, indicate masses that are merely a fraction of the central star's mass, perhaps a few percent or less. Theorists find this fact disturbing and challenging. For if the accumulation of collapsing material with excess rotation builds up disks, why should the process stop so soon after the star itself was formed? If indeed protostellar winds halt the collapse phase, do the small disk masses indicate a causal link between disk formation and the triggering of these energetic outflows?

Such questions still have no answers. But these unsolved problems should be viewed as gaps in a chain whose main links have already been forged, through an extraordinary interplay of experimental and theoretical work. We can close these gaps and complete the story of young stars if we can but read the clues nature has given. And those clues are right over our heads, winking in the clear night sky.

The Author

STEVEN W. STAHLER received his Ph.D. from the University of California, Berkeley, in 1980 and has held positions at Cornell University and the Harvard-Smithsonian Center for Astrophysics. Since 1985, he has been professor of physics at the Massachusetts Institute of Technology. Stahler writes that "this is an exhilarating time" for the study of young stars, likening the current state of

research to being in a darkroom as the image gradually appears--an apt metaphor, for he also pursues an avid interest in filmmaking. With Mary Barsony, he is writing "The Formation of Stars," to be published by Addison-Wesley in 1992.

Further Reading

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